Restoration of the Potosi Dynamic Model 2010

Topical Report

December 8, 2009 through June 30, 2014

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Report Issued: August 3, 2014

Report Number: DOE/FE0002068-13
U.S. DOE Cooperative Agreement Number: DE-FE0002068
An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

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1. Executive Summary

In topical Report DOE/FE0002068-1 [2] technical performance evaluations on the Cambrian Potosi Formation were performed through reservoir modeling. The data included formation tops from mud logs, well logs from the VW1 and the CCS1 wells, structural and stratigraphic formation from three dimensional (3D) seismic data, and field data from several waste water injection wells for Potosi Formation. Intention was for two million tons per annum (MTPA) of CO_2 to be injected for 20 years.

In this Task the 2010 Potosi heterogeneous model (referred to as the "Potosi Dynamic Model 2010" in this report) was re-run using a new injection scenario; 3.2 MTPA for 30 years. The extent of the Potosi Dynamic Model 2010, however, appeared too small for the new injection target. It was not sufficiently large enough to accommodate the evolution of the plume. Also, it might have overestimated the injection capacity by enhancing too much the pressure relief due to the relatively close proximity between the injector and the infinite acting boundaries.

The new model, Potosi Dynamic Model 2013a, was built by extending the Potosi Dynamic Model 2010 grid to 30 miles x 30 miles (48 km by 48 km), while preserving all property modeling workflows and layering. This model was retained as the base case.

Potosi Dynamic Model 2013.a gives an average CO_2 injection rate of 1.4 MTPA and cumulative injection of 43 Mt in 30 years, which corresponds to 45% of the injection target. This implies that according to this preliminary model, a minimum of three (3) wells could be required to achieve the injection target. The injectivity evaluation of the Potosi formation will be revisited in topical Report 15 during which more data will be integrated in the modeling exercise. A vertical flow performance evaluation could be considered for the succeeding task to determine the appropriate tubing size, the required injection tubing head pressure (THP) and to investigate whether the corresponding well injection rate falls within the tubing erosional velocity limit.

After 30 years, the plume extends 15 miles (24 km) in E-W and 14 miles (22 km) in N-S directions. After injection is completed, the plume continues to migrate laterally, mainly driven by the remaining pressure gradient. After 100 years post-injection, the plume extends 17 miles (27 km) in E-W and 15 miles (24 km) in N-S directions.

The increase of reservoir pressure at the end of injection is approximately 370 psia around the injector and gradually decreases away from the well. The reservoir pressure increase is less than 30 psia beyond 14 miles (22 km) away from injector. The initial reservoir pressure is restored after approximately 20 years post-injection. This result, however, is associated with uncertainties on the boundary conditions, and a sensitivity analysis could be considered for the succeeding tasks.

It is important to remember that the respective plume extent and areal pressure increase corresponds to an injection of 43 Mt CO_2. Should the targeted cumulative injection of 96 Mt be achieved; a much larger plume extent and areal pressure increase could be expected.

Re-evaluating the permeability modeling, vugs and heterogeneity distributions, and relative permeability input could be considered for the succeeding Potosi formation evaluations. A simulation using several injectors could also be considered to determine the required number of wells to achieve the injection target while taking into account the pressure interference.

2. Introduction

2.1. Context

This project is part of a larger project co-funded by the United States Department of Energy (US DOE) under cooperative agreement DE-FE0002068 from 12/08/2009 through 9/31/2013 [1]. The entire study was to evaluate the potential of formations within the Cambro-Ordovician strata above the Mt. Simon Sandstone as potential targets for carbon sequestration in the Illinois and Michigan Basins. The Illinois Clean Coal Institute (ICCI) requested Schlumberger to evaluate the potential injectivity and plume size of the Cambrian Potosi Formation. The evaluation of this formation was accomplished using wireline data, core data, pressure data, and seismic data from the US DOE funded Illinois Basin – Decatur Project being conducted by the Midwest Geological Sequestration Consortium in Macon County, Illinois.

In Topical Report DOE/FE0002068-1 [2], technical performance evaluations on the Cambrian Potosi Formation were performed through reservoir modeling. The data included formation tops from mud logs, well logs from the verification well (VW1) and the injection well (CCS1) wells, structural and stratigraphic formation from three dimensional (3D) seismic data, and field data from several waste injection wells for Potosi Formation. The Mt. Simon Sandstone was the target formation for the drilling of these wells. The intention was for 2 MTPA of CO_2 to be injected for 20 years.

In this task, the 2010 Potosi heterogeneous model [2] (referred to as "Potosi Dynamic Model 2010" in this report) will be re-run using a new injection scenario; 3.2 MTPA for 30 years. Increasing the model extent could be required as the plume got close to the reservoir boundary in the 2010 model.

2.2. Objectives

The objectives of the task are to:

- Re-run the Potosi Dynamic Model 2010 with the new injection scheme; 3.2 MTPA for 30 years,
- Increase the model extent if necessary, and re-run simulation with the new injection scheme, continued by 100 years post injection period,
- Evaluate the injection profile, plume extent, and areal pressure increase.

2.3. Scope

Only the Potosi heterogeneous model will be evaluated. All 2010 modeling assumptions [2] will be retained.

3. Potosi Dynamic Model Restoration

3.1. Potosi Dynamic Model 2010

3.1.1. Assumptions

In order to evaluate the injectivity and capacity of the Potosi formation, a number of data sets were integrated and reservoir modeling was performed. Data included formation tops from mud logs, well logs from VW1 drilled by the Illinois State Geological Survey in 2010 and the CCS1 well, structural and stratigraphic information from three-dimensional (3D) seismic data, and field data from several waste injection wells [2]. Formation injectivity and capacity were analyzed by placing an imaginary well where the CCS1 well is located.

3.1.1.1. Simulation Grid

The geocellular model covered a 10 mile x 10 mile (16 x 16 km) lateral area and a 430 foot (131 m) thick formation. The reservoir was represented with a 112 x112 x70 grid (Figure 3-1). Around the wellbores each grid cell is as small as 190 feet x190 feet (58 m x 58 m) (aerially, whereas grid cells close to the model boundaries are as big as 1,500 feet x 1,500 feet (457 m x 457 m) with a layer thickness ranging between 3 feet (1 m) and 12 feet 3.6 m) [2].

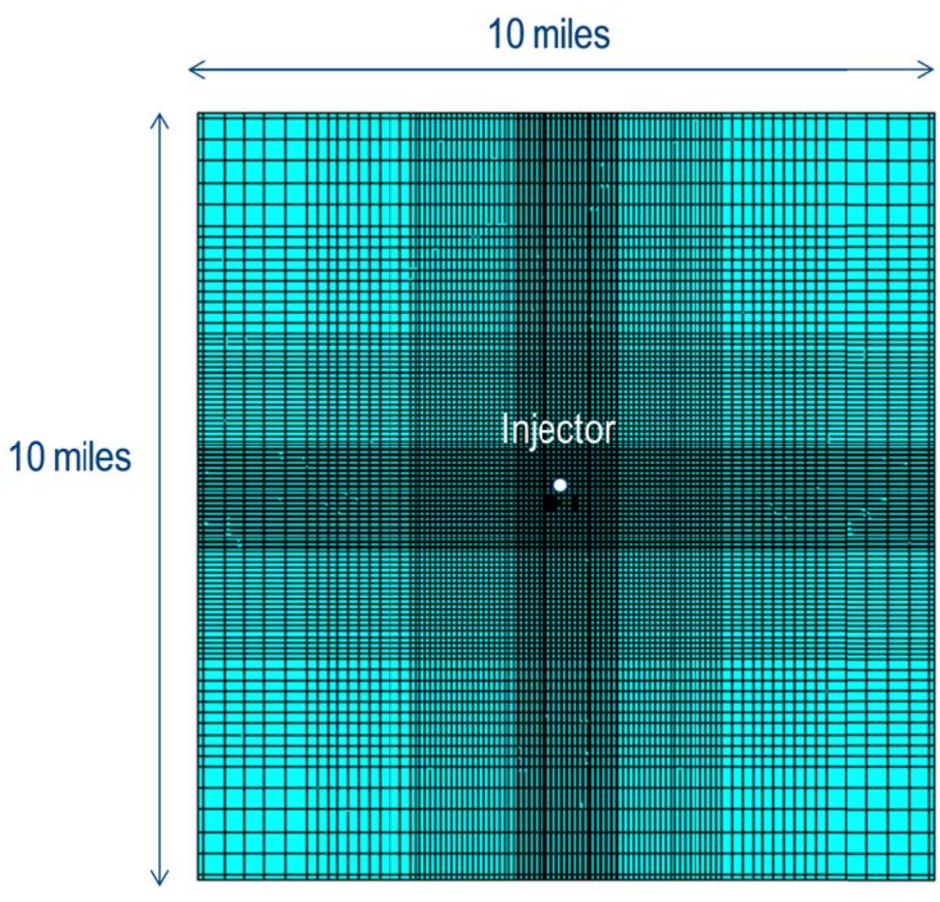

Figure 3-1 Potosi Dynamic Model 2010 – Grid Top View

3.1.1.2. Porosity and Permeability

Porosity and permeability were populated based on CCS1 and verification well log data [2]. Permeability was upscaled to the simulation model using volume-weighted harmonic averaging. Porosity was upscaled to the simulation model using volume-weighted arithmetic averaging (Figure 3-2 and Figure 3-3). Information from both wells was propagated throughout the model with Sequential Gaussian simulation to create the heterogeneous model (Figure 3-4 and Figure 3-5). No core data or well test data was available on vertical permeability hence is assumed to be 30% of horizontal permeability [2]. Due to the vugular nature of the carbonate reservoir, log-derived permeability data was modified utilizing the formula below to attempt to approximate behavior observed in Potosi waste injection wells and during drilling of the CCS1 well [2]. Through this transform, the initially calculated permeability ($k_{initial}$), which responds primarily to matrix porosity, was modified to account for the proportion of porosity attributable to vugs.

$$k_{modified} = k_{initial} \times (1+2 \times \phi_{Total}) \qquad [2]$$

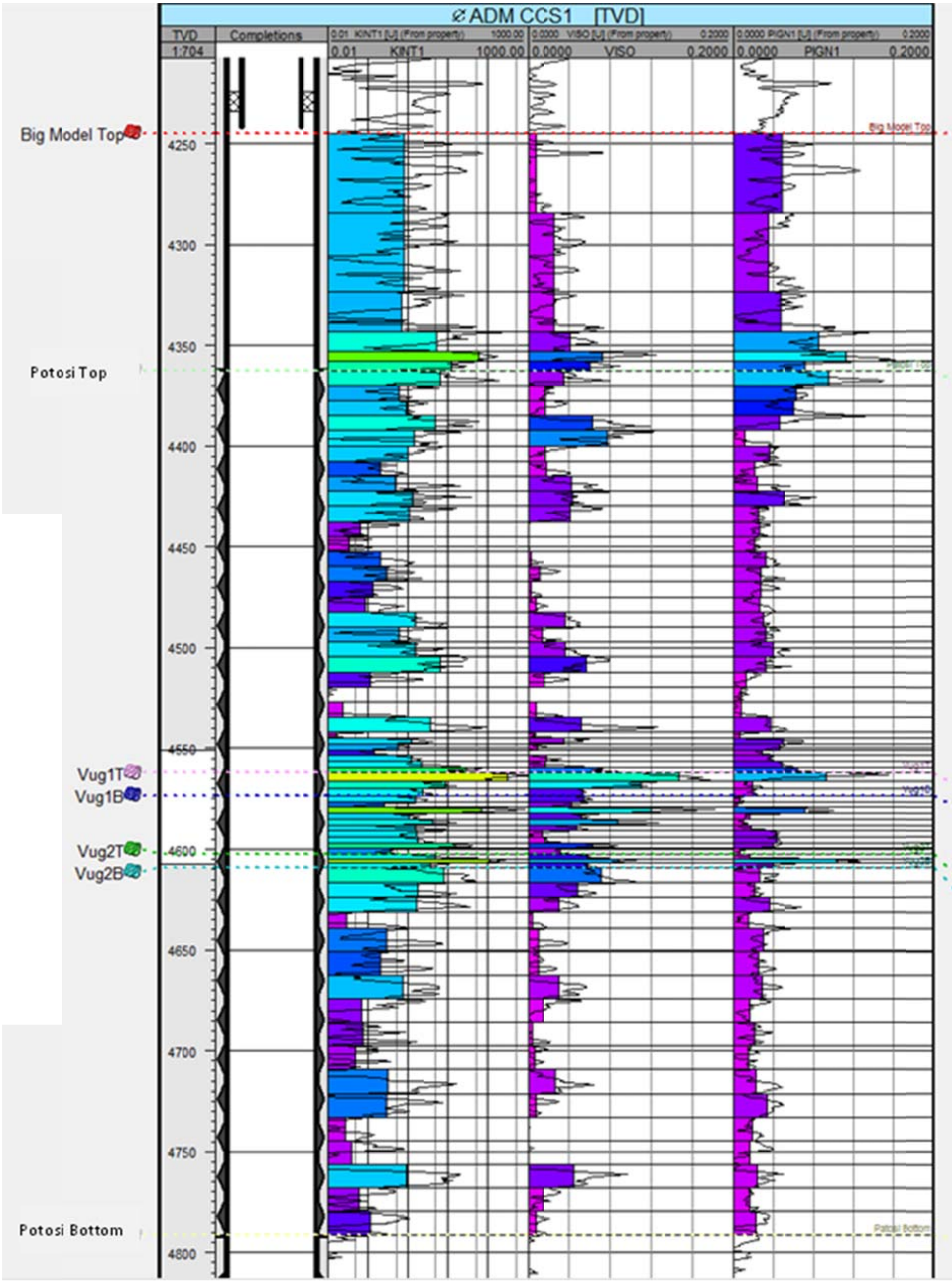

Figure 3-2 CCS1 well completions and layering schematic with corresponding permeability, total porosity and net porosity [2].

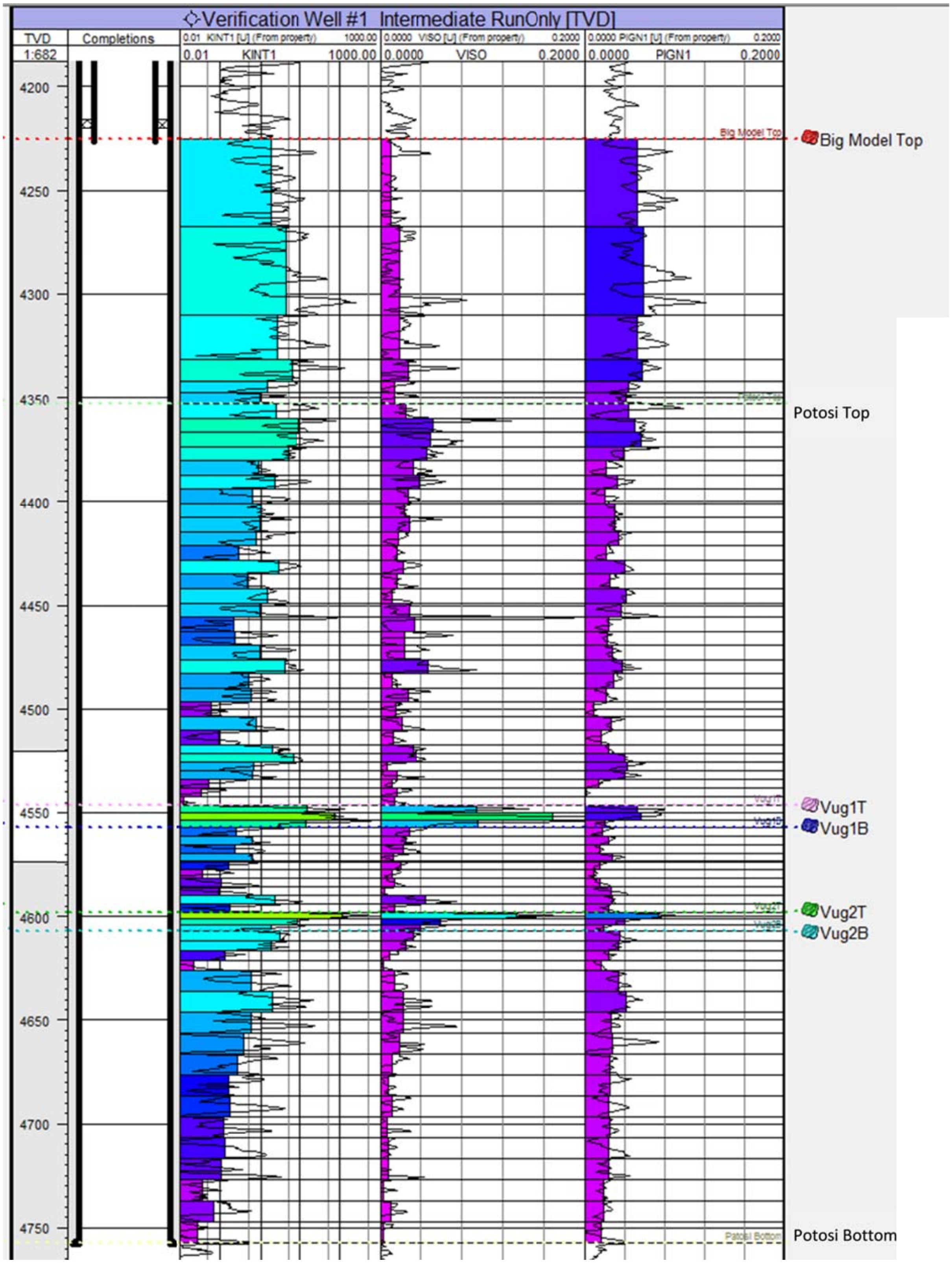

Figure 3-3 VW1 completions and layering schematic with corresponding permeability, total porosity and net porosity [2].

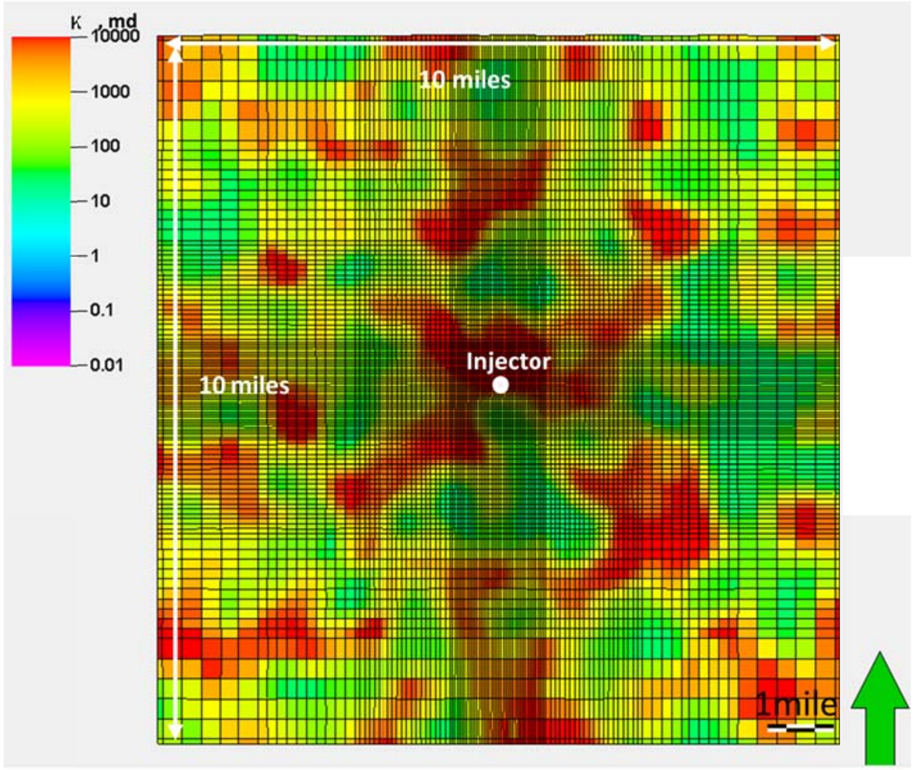

Figure 3-4 Potosi Dynamic Model 2010, layer permeability of a vugular layer [2]

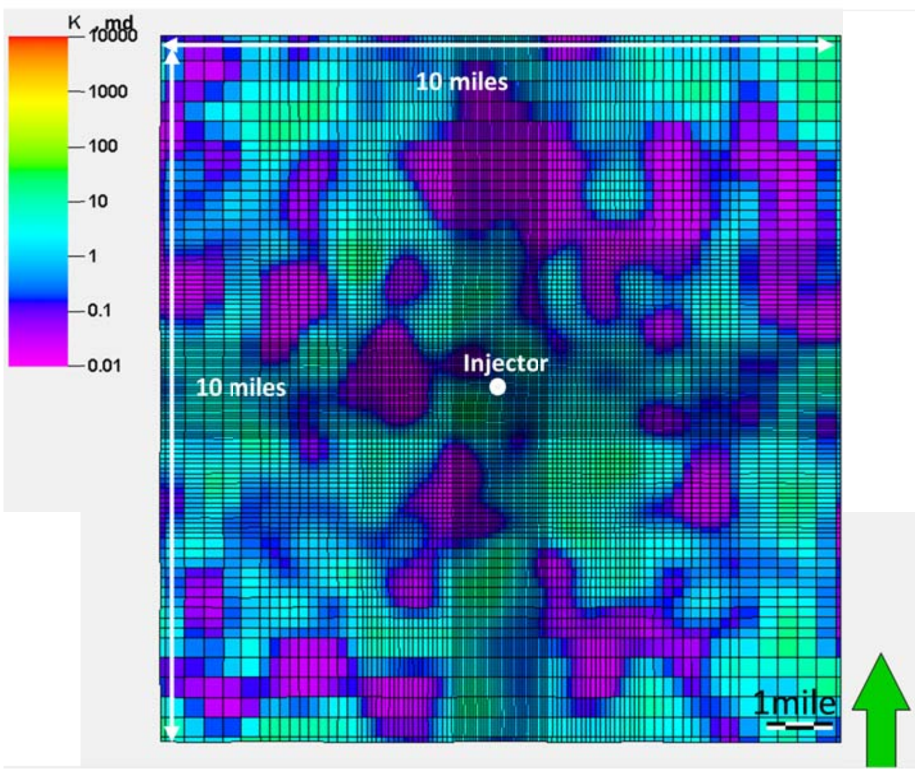

Figure 3-5 Potosi Dynamic Model 2010, layer permeability of a non-vugular layer [2]

3.1.1.3. Fluid Properties

The reservoir was assumed to be 100% brine saturated with an initial formation salinity of 10,000 ppm [2]. For modeling purposes, the injected gas is assumed to have the behavior of pure CO_2. Due to the absence of special core analysis (SCAL) data, relative permeability curves were generated using in-house software (Figure 3-6) [2]. Residual water and CO_2 saturations are assumed to be 25% and 20% respectively.

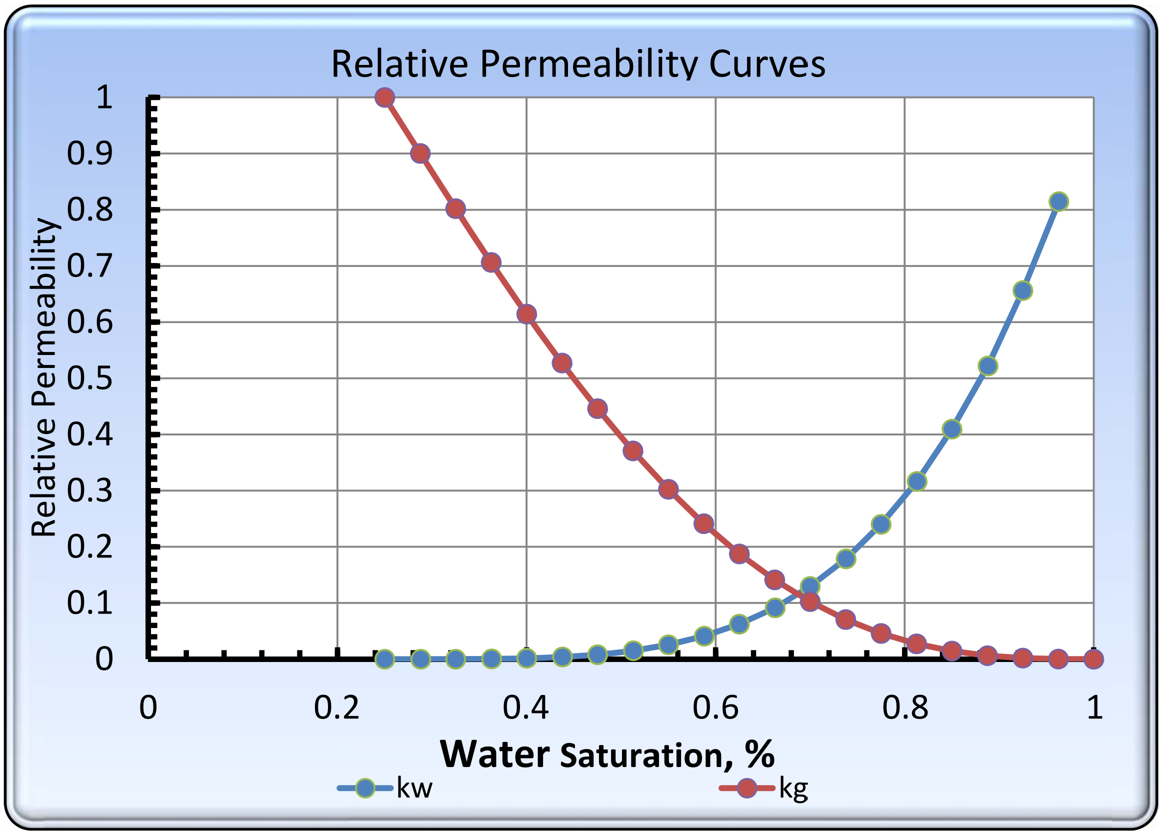

Figure 3-6 Potosi Dynamic Model 2010, Relative permeability curves [2]

3.1.1.4. Model Equilibration

The model was equilibrated as a slightly under-pressured reservoir (0.42 psi/ft based on MDT data) with a reference pressure of 1,932 psia at 4,600 ft (1402 m) [2]. Reservoir temperature, measured with distributed temperature sensing (DTS), was constant in the reservoir at 97^oF [2].

3.1.1.5. Reservoir Boundaries

Infinite-acting conditions were assumed at the lateral boundaries of the simulation model. This was modeled by applying a pore multiplier of 10^4 in the cells at the model parameters to account for a larger aquifer volume. These infinite-acting boundaries would act as pressure sinks during and after the injection.

Only the Potosi formation is included in the model. No flow boundary assumed at the top and bottom of the model.

3.1.1.6. Injection Constraints

The entire 430 feet of the Potosi formation was assumed to be perforated for simulating CO_2 injection. Injection was carried out between 4,361 feet (1329 m) and 4,791 feet (1460 m) [2].

Intention was for 3.2 MTPA of CO_2 to be injected for 30 years. A single injection well was controlled by maximum allowable bottomhole injection pressure (BHP) of 2,320 psi at 4,640 feet (1414 m). A 0.5 psi/ft pressure gradient was assumed to keep the expected tubing head pressure low as observed in area waste water injection wells [2].

The limitation of tubing deliverability is neglected in this analysis. The tubing size is assumed to be sufficiently large to inject the rate predicted by the simulation.

3.1.2. Results

Potosi Dynamic Model 2010 indicates that the targeted injection rate (3.2 MTPA) could not be achieved before the end of the injection (Figure 3-7). The well injection rate is constrained by the maximum allowable BHP. It increases from approximately 2 MTPA at the start of the injection up to 3.2 MTPA just before injection ends, as the CO_2 relative permeability in the near wellbore area increases with the decrease in the irreducible water saturation due to dry out (water vaporizes into the CO_2 rich phase). The estimated cumulative injection after 30 years is approximately 80 million tons (Mt) (83% of the target). Again, this was achieved by overlooking the tubing size constraint.

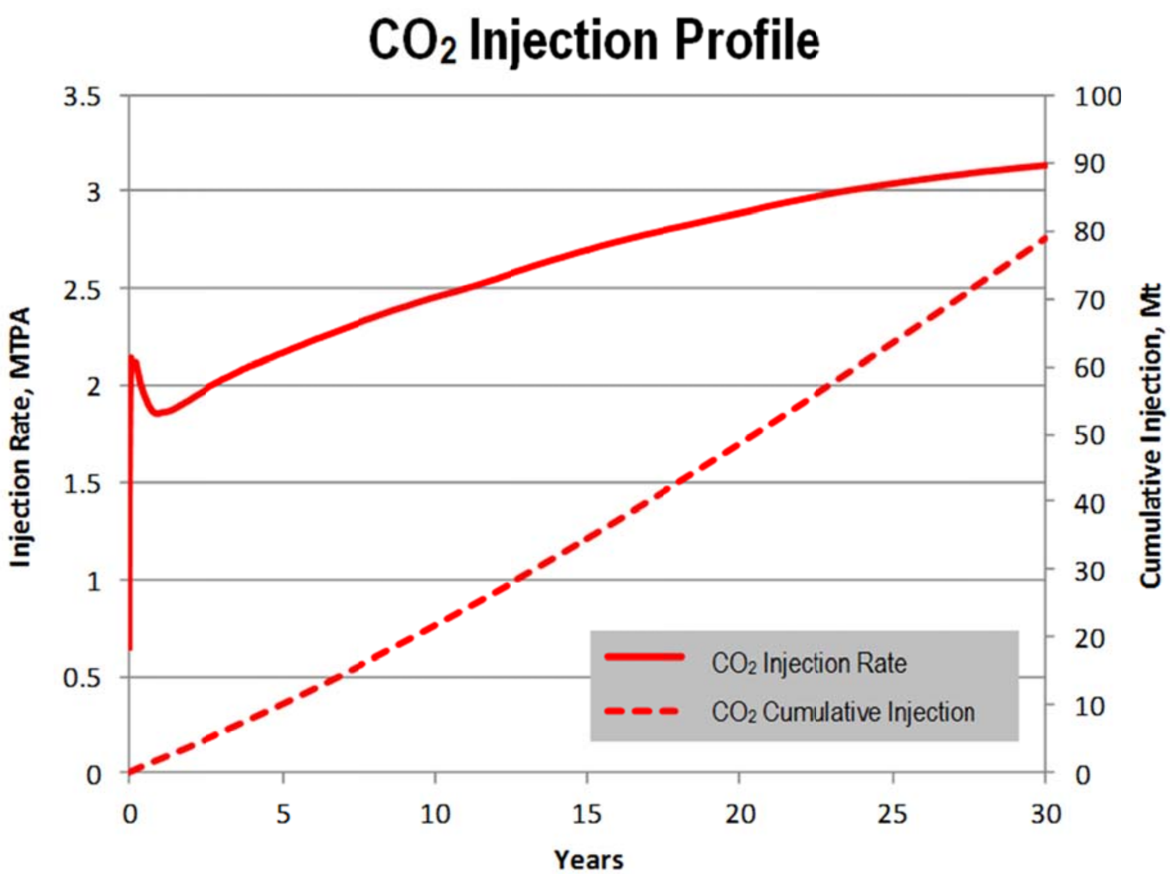

Figure 3-7 Potosi Dynamic Model 2010, estimated injection rate and cumulative injection vs. time

CO_2 preferentially flows into and through thin high permeability vugular intervals, resulting in a large plume radius. Figure 3-8 shows that the plume reaches the model parameters after 10 years of injection (20 Mt of cumulative injection). This indicates that the existing model extent is not sufficient to evaluate the respective plume extent. Inappropriate model size could also lead to an incorrect estimation of injection rate and pressure evolutions. This leads to a conclusion that the Potosi Dynamic Model 2010 is not suitable for the intended injection scheme and thus inapplicable for the current evaluation.

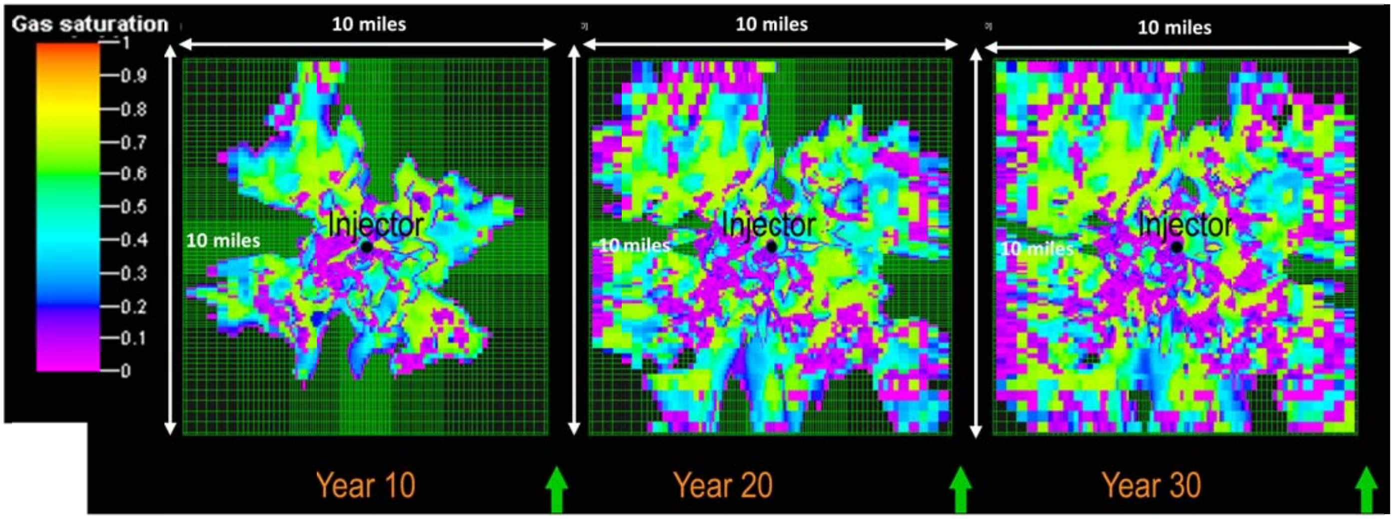

Figure 3-8 Potosi Dynamic Model 2010, plume extent during injection

3.2. Potosi Dynamic Model 2013.a

3.2.1. Assumptions

The Potosi Dynamic Model 2013.a is built to replace the Potosi Dynamic Model 2010 in which extent is not sufficient for the current evaluation. This model was derived from the Potosi Dynamic Model 2010 by applying the following steps:

- The grid is extended to 30 miles x 30 miles (48 km x 48 km) (nine times larger than the Potosi Dynamic Model 2010). This was done by extrapolating surfaces and re-gridding. Grid size ranges from 150 feet x 150 feet (46 m x 46 m) around injector CCS1 and gradually coarsens to 4800 feet x4800 feet (1463 m x 1463 m) at model parameters.
- Layering is preserved and thus identical to Potosi Dynamic Model 2010.
- Property is modeled by using the same data and workflow as Potosi Dynamic Model 2010. The same porosity and permeability distribution is preserved, but the property coordinates within the model will be different. Figure 3-9 and Figure 3-10 describes the permeability populations in the non-vugular and vugular layers, respectively.
- Infinite acting boundaries are assigned at the lateral parameters by applying a pore volume multiplier.
- Reservoir pressure, temperature, fluid properties, relative permeability, and injection constraints assumed are equivalent to Potosi Dynamic Model 2010.

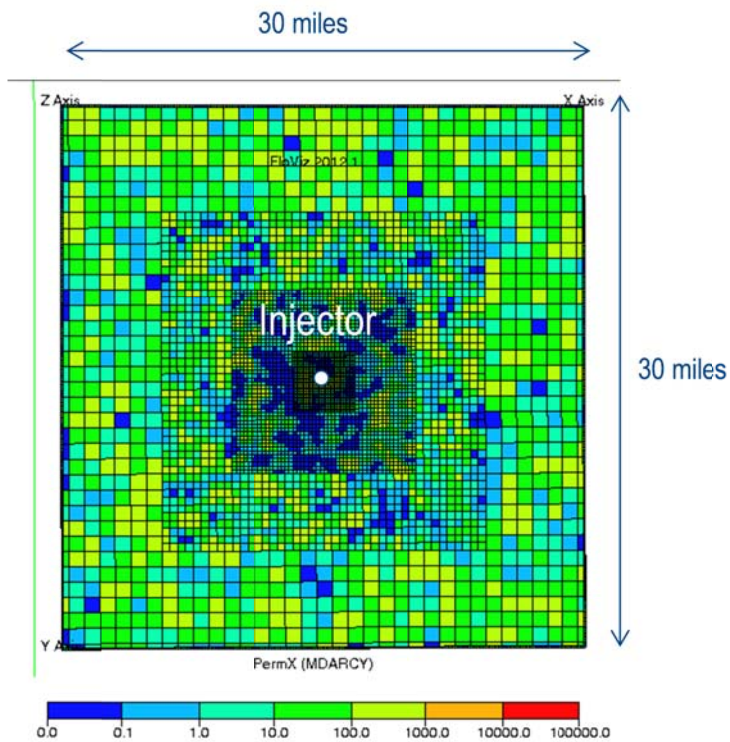

Figure 3-9 Potosi Dynamic Model 2013a, layer permeability of a non-vugular layer

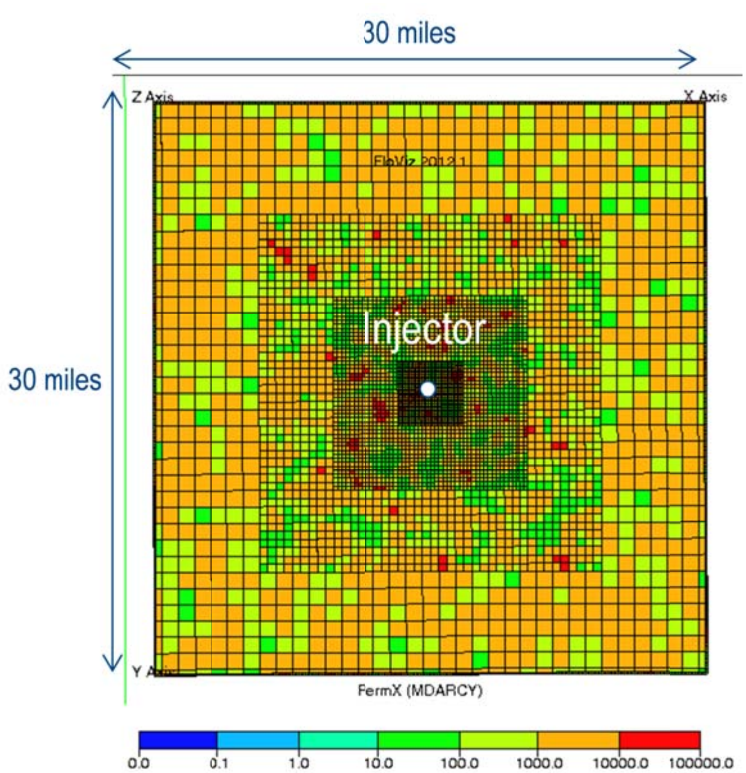

Figure 3-10 Potosi Dynamic Model 2013a, layer permeability of a vugular layer

Two cases were simulated:

- The base case: Potosi Dynamic Model 2013.a with an extent of 30 miles x 30 miles (48 km x 48 km)
- A sensitivity case: Potosi Dynamic Model 2013.a with an extent of 10 miles x 10 miles (16 km x 16 km) extent (cells beyond 5 miles (8 km) radius from the injector are deactivated) to evaluate the impact of pressure sink distance from the injector and to verify whether the model response is similar to Potosi Dynamic Model 2010

3.2.2. Results

Injection Profile

Figure 3-11 and Figure 3-12 allows the comparison between the injection rate and well bottom-hole pressure (WBHP) profiles of Potosi Dynamic Model 2010, Potosi Dynamic Model 2013a with a 10 mile x10 mile (16 km x 16 km) extent, and Potosi Dynamic Model 2013a with a 30 mile x 30 mile (48 m x 48 m) extent, which is regarded as the base case. Figure 3-11 and Figure 3-12 indicate that Potosi Dynamic Model 2013.a with a 10 mile x 10 mile (16 km x 16 km) extent gives a similar injection result as the Potosi Dynamic Model 2010, which implies that the two models align regardless of the different property realizations. However, Potosi Dynamic Model 2013.a with a 30 mile x 30 mile (48 km x 48 km) extent shows a two times smaller injection rate and cumulative injection. The bigger model appears to have a slower pressure relief due to a much further distance between the injector and the pressure sink in model parameters, and since a much larger area is exposed to the heterogeneity.

This confirms that a 10 mile x 10 mile (48 m x 48 m) extent is too small for the Potosi dynamic model and the respective injection target as the pressure relief might be enhanced. Further evaluation in the Potosi Formation should be performed using a larger model extent. The Potosi Dynamic Model 2013.a with a 30 mile x 30 mile (48 km x 48 km) extent is retained as the Task base case.

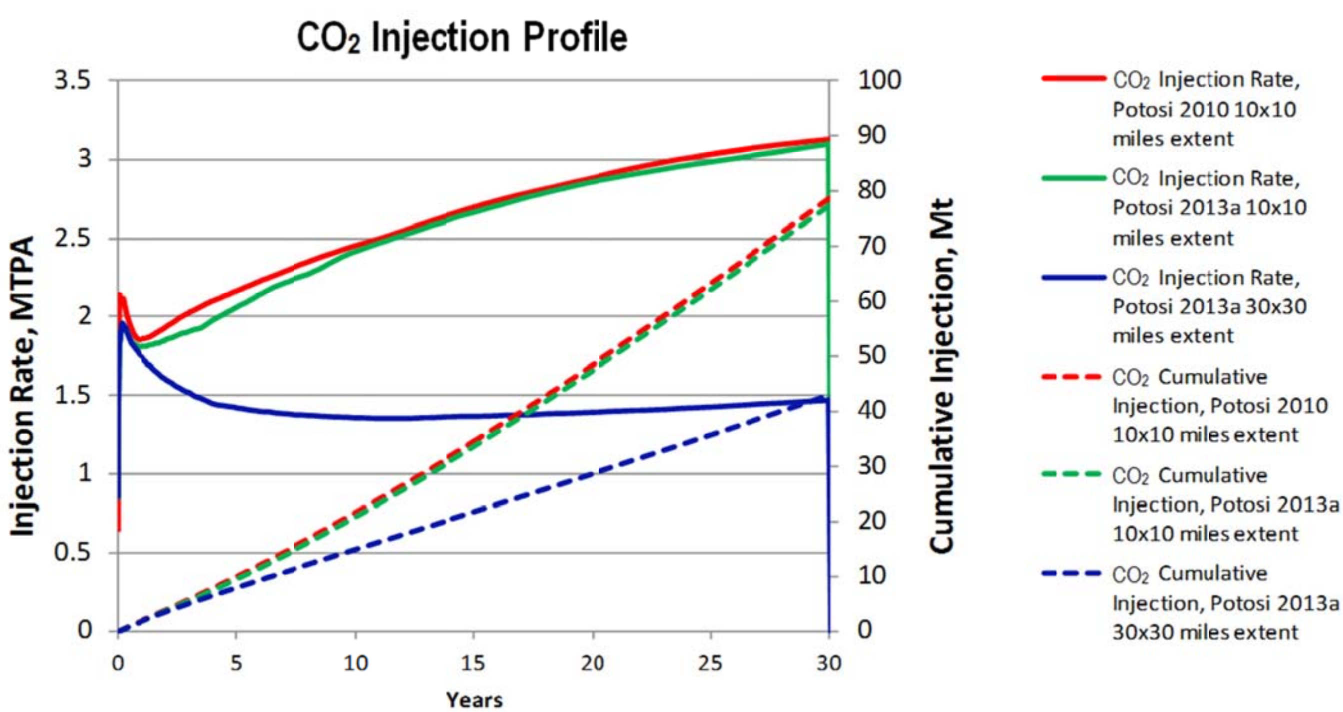

Figure 3-11 Potosi Dynamic Model 2010, estimated injection rate and cumulative injection vs. time

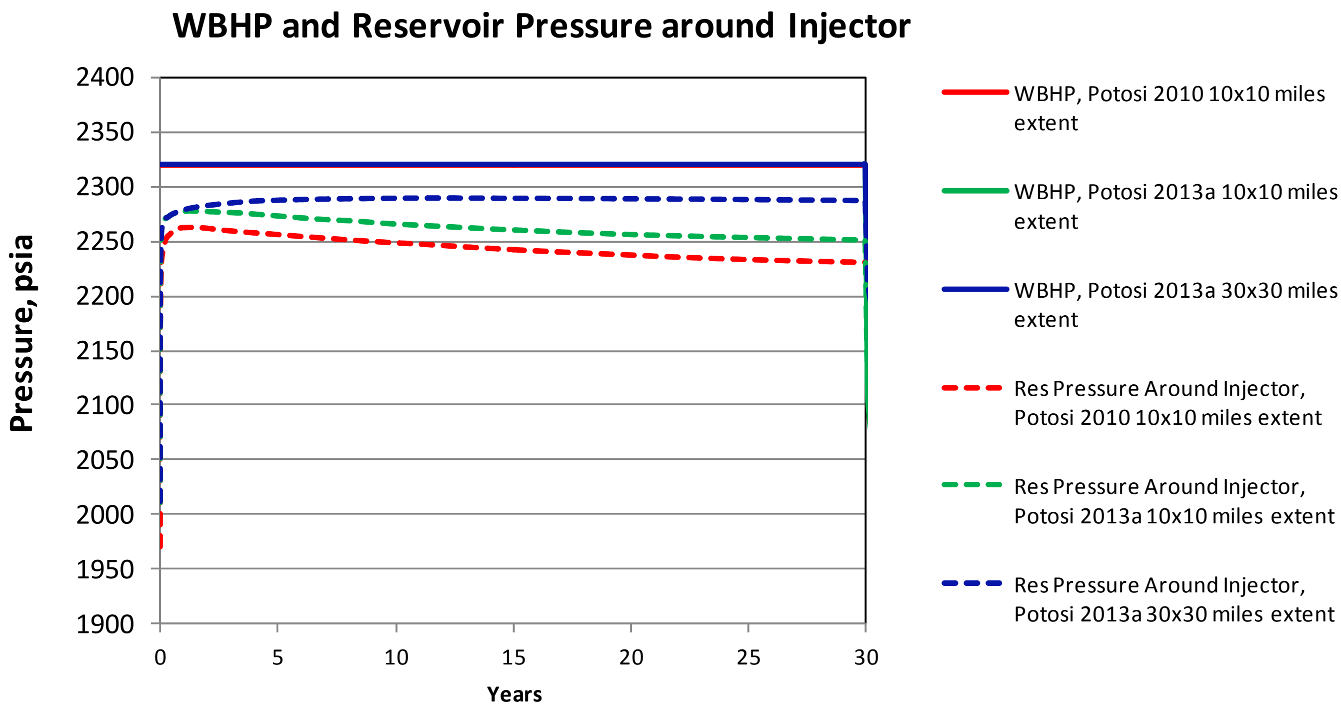

Figure 3-12 Potosi Dynamic Model 2010, WBHP and reservoir pressure around injector vs. time

Figure 3-11 indicates that for the base case, the targeted injection rate (3.2 MTPA) could not be achieved during the entire injection period using only one well. The well injection rate is constrained by the maximum allowable BHP (Figure 3-12). It decreases from approximately 2 MTPA at the start of the injection down to 1.4 MTPA after five years as the reservoir pressure increases. It gradually increases and reaches 1.5 MTPA just before injection is completed, as a dry out effect slightly enhances the injectivity. The estimated cumulative injection after 30 years is approximately 43 Mt (45% of the target). This implies that a minimum of three injector wells could be necessary. A vertical flow performance evaluation could be considered to determine the appropriate tubing size, the required injection THP and to investigate whether the corresponding well injection rate falls within the tubing erosional velocity limit.

This result, however, will be revisited when more data can be integrated into the modeling exercise.

Plume Extent

Similar to Potosi Dynamic Model 2010, CO_2 flows preferentially into and through thin vugular intervals, and hence creates a reasonably large plume extent. After 30 years, the plume extends 15 miles (24 km) in E-W and 14 miles (22 km) in N-S directions (Figure 3-13). After injection is completed, the plume continues to migrate laterally, mainly driven by the remaining pressure gradient. After 100 years post-injection, the plume extends 17 miles (27 km) in E-W and 15 miles (24 km) in N-S directions (Figure 3-13). Should the targeted cumulative injection of 96 Mt be achieved; a much larger plume extent could be expected.

Driven by gravity force, some CO_2 migrates vertically across layers and reach the top of the formation. It did not, however, change the plume shape significantly during 100 years post injection (Figure 3-14). As the permeability of the vugular layers is much higher than the non-vugular layers, the plume remains within the vugular layers and migrates laterally.

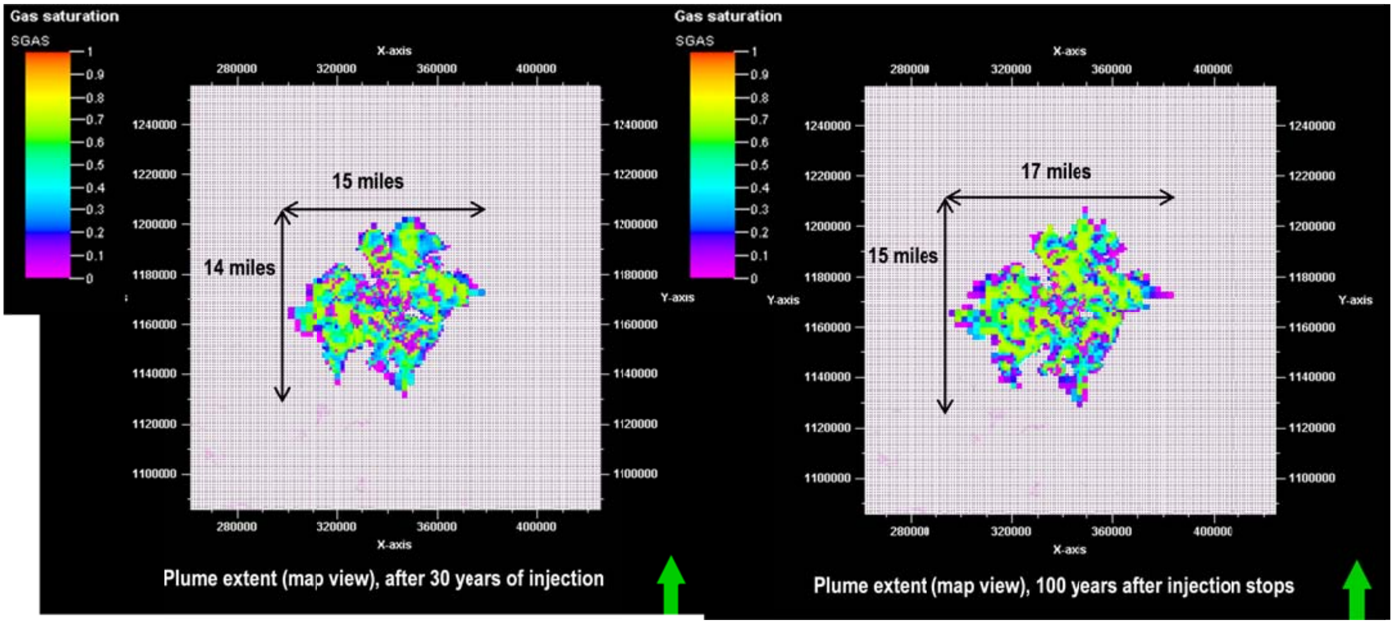

Figure 3-13 Potosi Dynamic Model 2013a, plume extent, top view.
Left: after 30 years of injection. Right: 100 years post-injection

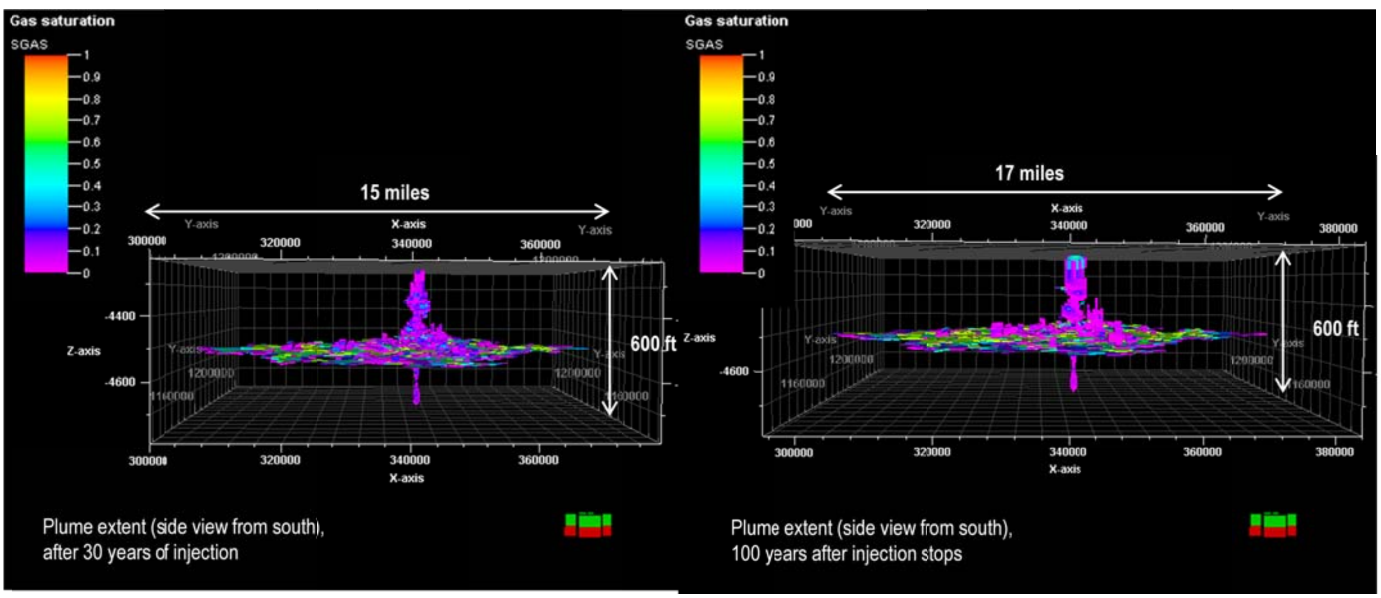

Figure 3-14 Potosi Dynamic Model 2013a, plume extent, side view (from south).
Left: after 30 years of injection. Right: 100 years post-injection

Pressure Evolution

Figure 3-15 indicates that the reservoir pressure increase at the end of injection is approximately 370 psia around the injector and gradually decreases away from the well. The reservoir pressure increase at the end of injection is less than 30 psia beyond 14 miles (22 km) from the injector. The injection leads to a pressure increase in a large area due to the low compressibility of the aquifer system. Should the targeted cumulative injection of 96 Mt is achieved; a much larger areal pressure increase could be expected.

After injection stops, the pressure stabilized gradually due to infinite acting boundary in the parameters of the dynamic model, which pushes out the water in the reservoir. Figure 3-15 and Figure 3-16 show that the initial reservoir pressure is restored after approximately 20 years post-injection. This result, however, is associated to uncertainties on the boundary conditions and a sensitivity analysis could be considered for the succeeding tasks.

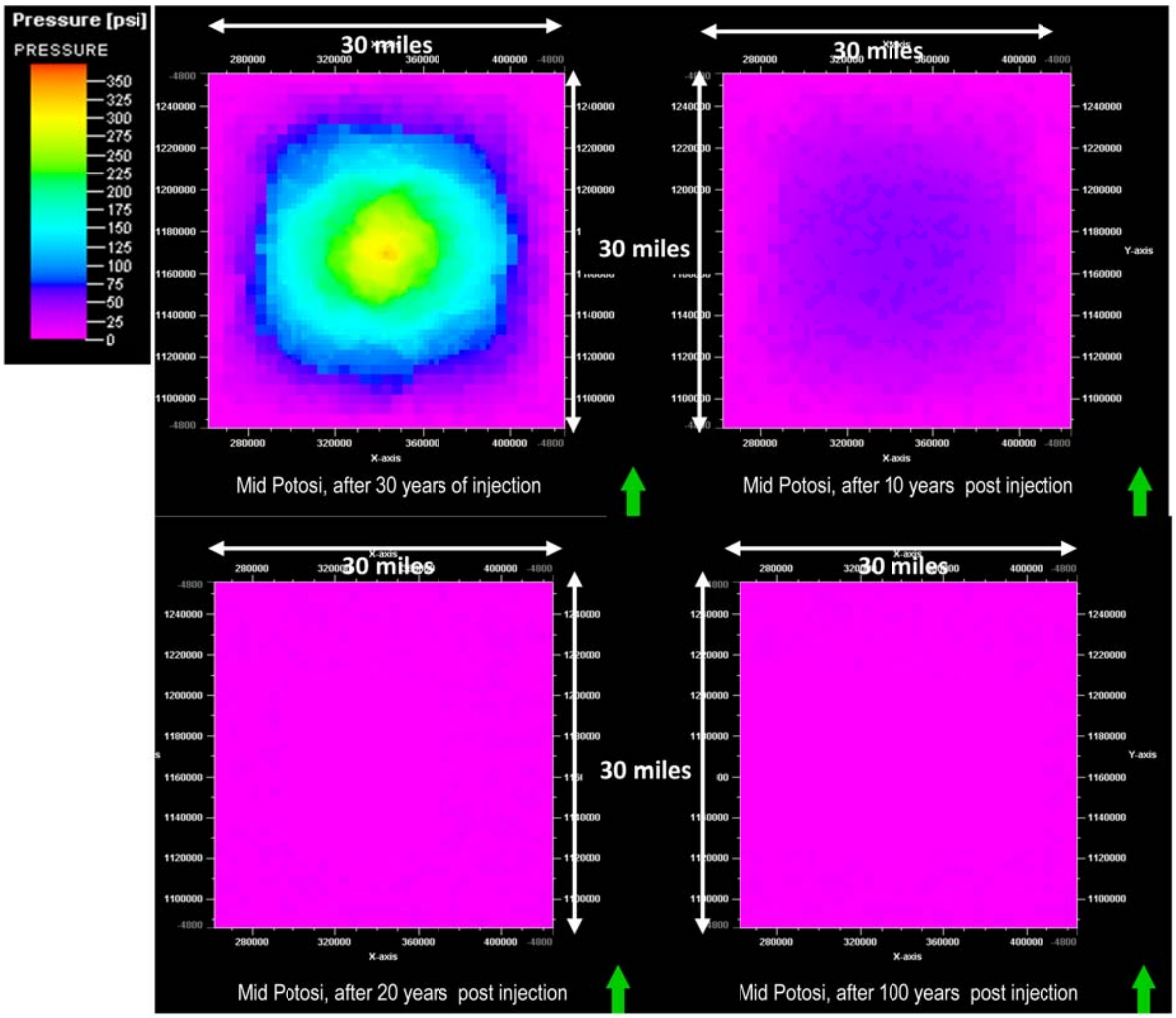

Figure 3-15 Potosi Dynamic Model 2013a, areal pressure increase, top view.
Top left: after 30 years of injection.
Top right: 10 years post-injection.
Bottom left: 20 years post-injection.
Bottom left: 100 years post-injection.

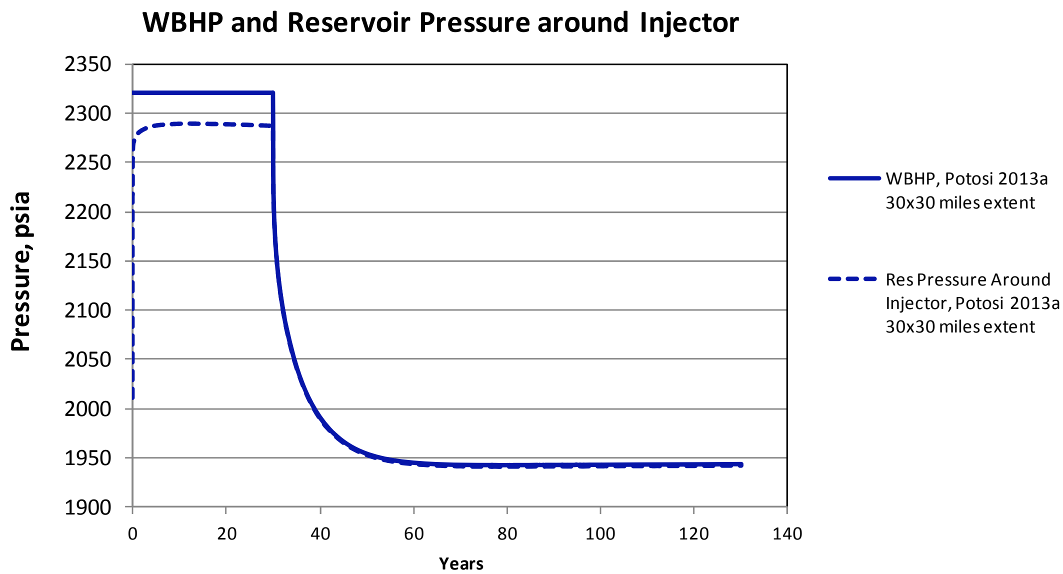

Figure 3-16 Potosi Dynamic Model 2013a, WBHP and reservoir pressure around injector, during 30 years of injection and 100 years post-injection.

4. Conclusions and Recommendations

4.1. Conclusions

Evaluation of the Potosi formation CO_2 storage performance has been done using a derivation of 2010 modeling workflow. The following can be concluded:

- The extent of Potosi Dynamic Model 2010 appears too small for the new injection target. It is not sufficient to accommodate the evolution of the plume. Also, the injection capacity might have overestimated by enhancing the pressure relief due to the relatively close distance between the injector and the infinite acting boundaries.
- The new model Potosi Dynamic Model 2013a was built by extending the Potosi Dynamic Model 2010 grid to 30 miles x 30 miles, (48 km x 48 km) while preserving all property modeling workflows and layering. This model is retained as the base case.
- Potosi Dynamic Model 2013.a gives an average CO_2 injection rate of 1.4 MTPA and cumulative injection of 43 Mt in 30 years, which corresponds to 45% of the injection target. This implies that according to this preliminary model, a minimum of 3 wells could be required to achieve the injection target. This result, however, did not take into account the limitation of the tubing deliverability. The injectivity evaluation of the Potosi formation will be revisited when more data could be integrated into the modeling exercise.
- After 30 years, the plume extends 15 miles (24 km) in E-W and 14 miles (km) in N-S directions. After injection finishes, the plume continues to migrate laterally, mainly driven by the remaining pressure gradient. After 100 years post injection, the plume extends 17 miles (27 km) in E-W and 15 miles (24 km) in N-S directions. Should the targeted cumulative injection of 96 Mt be achieved; a much larger plume extent could be expected.
- The increase of reservoir pressure at the end of injection is approximately 370 psia around the injector and gradually decreases away from the well. The reservoir pressure increase is less than 30 psia beyond 14 miles (22 km) away from injector. Should the targeted cumulative injection of 96 Mt is achieved; a much larger areal pressure increase could be expected. The initial reservoir pressure is restored after approximately 20 years post injection. This result, however, is associated to uncertainties on the boundary conditions, and thus a sensitivity analysis could be considered for the succeeding tasks

4.2. Recommendations

Revisiting the following points could be considered for the succeeding Potosi formation evaluations:

- The current permeability was derived from well logs and modified using an empirical equation to match the drilling loss rate. This permeability modifier could be re-evaluated should the core analysis data be available.
- The relative permeability used in the current task is arbitrary due to the limited sources on such data. The relative permeability input could be reviewed should the core analysis data be available. Otherwise, published sources on CO_2-brine relative permeability could be referred.
- The property modeling in Potosi formation is associated to uncertainties on vugs distribution and interconnectivity within the reservoir and thus two different realizations could be considered;
    - First realization with the presence of vugular layers where the vugs are relatively large and interconnected.
    - Second realization with smaller vugs and less interconnectivity between them.

  Also, this 2010 modeling workflow uses a big variogram range and thus could be re-visited in the next task.
- The injectivity estimation in Potosi formation is associated to uncertainties on permeability distribution and boundary conditions. Sensitivity analysis on permeability and boundary conditions could be considered in the succeeding evaluations.

- A vertical flow performance evaluation could be considered for the succeeding task to determine the appropriate tubing size, the required injection THP and to investigate whether the corresponding well injection rate falls within the tubing erosional velocity limit.
- A simulation using several injectors could also be considered to determine the required number of wells to achieve the injection target while taking into account the pressure interference.

5. References

[1] Leetaru, H.E., A.L. Brown, D.W. Lee, O. Senel, and M. Couëslan, 2012, CO2 Injectivity, storage capacity, plume size, and reservoir and seal integrity of the Ordovician St. Peter Sandstone and the Cambrian Potosi Formation in the Illinois Basin. USDOE Topical Report, Report Number DOE/FE0002068-1, 29 p.

[2] Senel, O., 2010, *Results of Reservoir Simulation Study for St. Peter & Potosi Formations*. Schlumberger Carbon Services, October 2010.